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(MANTECH) PROGRAM

ULTRASONIC COLD FORMING OF AIRCRAFT SHEET MATERIALS

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FINAL REPORT

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U.S. ARMY AVIATION RESEARCH AND DEVELOPMENT COMMAND

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Ultrasonic forming was investigated as a means for shaping aircraft sheet materials, including titanium 6Al-4V alloy, nickel, and stainless steel AM355-CRT, into a helicopter rotor blade nosecap contour. Equipment for static forming of small coupons consisted of a modified 4000-watt ultrasonic spot welder provided with specially designed punch and die sets. The titanium alloy was successfully formed to a 60-degree angle in one step with

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ultrasonics, but invariably cracked under static force alone. Nickel had a low enough yield strength that it could be successfully formed either with or without ultrasonics. Insufficient ultrasonic power was available to produce beneficial effect with the high-strength steel. From analogy with commercially used ultrasonic tube drawing, it was postulated that dynamic forming of long lengths of the nosecap geometry could be achieved with an ultrasonic system mounted on a drawbench. It was recommended that the ultrasonic technique be considered for forming other aircraft sheet geometries, particularly involving titanium alloy.

PREFACE

This report on ultrasonically assisted forming of aircraft parts was prepared by Sonobond Corporation, West Chester, PA, under Army Contract DAAG46-79-C-0001. This project was accomplished as part of the US Army Aviation Research and Development Command Manufacturing Technology program. The primary objective of this program is to develop, on a timely basis, manufacturing processes, techniques, and equipment for use in production of Army materiel. Comments are solicited on the potential utilization of the information contained herein as applied to present and/or future production programs. Such comments should be sent to: US Army Aviation Research and Development Command, ATTN: DRDAV-EGX, 4300 Goodfellow Boulevard, St. Louis, MO 63120.

Mr. Arthur M. Ayvazian of the Army Materiels and Mechanics Research Center, ATTN: DRXMR-AP, Watertown, MA, served as Contracting Officer's Representative on this project. The work at Sonobond was under the technical supervision of Mrs. Janet Devine, and Philip C. Krause served as administrative supervisor.

Assistance in the program was provided by Hughes Helicopters, Division of Summa Corporation, Culver City, CA, with Kenneth Niji providing technical liaison.

The findings of this report are not to be construed as an official Department of the Army position.

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INTRODUCTION

The objective of this program was to apply ultrasonic energy to the processing of aircraft sheet materials as a means of improving the forming and processing of helicopter rotor blade nosecaps. The metals of particular interest were nickel 200, 6Al-4V titanium alloy, and AM355-CRT stainless steel.

Ultrasonic activation has been demonstrated to produce significant benefits in the cold forming of metals, such as decrease in static force requirement, increasing in processing rates, reduction in the number of processing steps, and improvement in product quality, particularly in surface finish and dimensional tolerances. Such effects have been unmistakably demonstrated in such ultrasonic deformation processes as forging, extrusion, tube, rod, and wire drawing.

This type of cold forming could have a decided impact on the fabrication of helicopters. The cost effectiveness of the process would be reflected almost immediately in the production of various sheet metal shapes, and in particular the nosecap of the helicopter rotor blade. In this program, ultrasonic activation was examined as a technique to minimize incipient cracks, reduce springback, improve repeatability of the blade geometry, and maintain high fatigue strengths.

The contract initially called for a three-phase program. Phase I involved the development of a static ultrasonic forming system and its evaluation in forming of an AAH helicopter blade contour, with optimization of the independent parameters and evaluation of the quality of the ultrasonically formed materials. Phase II was oriented to extending the process to ultrasonic dynamic forming of nosecap specimens on a drawbench using a single module ultrasonic system, and Phase III involved further evaluation of the dynamic process with a triad ultrasonic system.

During the conduct of Phase I, rapid development was made in composite blade materials as a replacement for metal in the fabrication of helicopter rotor blades. For this reason, and due to cost escalation for Phases II and III, the Government elected to consider the work complete at the conclusion of the first phase.

CONVENTIONAL NOSECAP FORMING PROCESSES

Most rotor blades presently in service throughout the world use metallic sheet that has been hot formed for the

leading edge erosion-resistant nosecap. Ordinarily the nosecap is stainless steel, titanium alloy, or nickel. These materials are expensive, and the forming is usually a slow, costly process, sometimes involving high temperatures which degrade the surfaces. For example, the forming of titanium alloy sheet material into aeronautical surfaces is usually accomplished at 1400° to 1600° F. Expensive chemical agent and cleaning procedures are required to restore the titanium surfaces after such heating.

Titanium also exhibits springback during the sheet forming process. This springback involves elastic recovery of the metal, which is usually a function of the elastic strain present in the total deformation. Many attempts have been made to describe the forming process theoretically and to accurately predict springback for a variety of materials under forming conditions. If sufficient stress is applied to exceed the elastic limit and eliminate springback, the metal has a tendency to crack.

Ultrasonic cold forming would minimize the required cleaning procedures, and would be expected to reduce springback, reduce incipient cracking, improve the repeatability of blade geometry, and maintain high fatigue strengths.

BACKGROUND OF ULTRASONIC METAL FORMING

The potential payoff for ultrasonic cold forming of metals has a solid basis in past experimental and production activities. The beneficial effects have been unmistakably demonstrated in both tension and compression forming processes: tube, wire, and rod drawing; stretch forming, as in deep drawing, draw ironing, tube flaring, and dimpling; primary metal working by rolling and extrusion; and bending and straightening.

The discovery that metals deform more readily under ultrasonic influence dates back to the mid-1950's,* when fine metal wires stressed in tension with ultrasonic activation showed substantial reduction in yield strength and increase in elongation. The magnitude of the effect was independent of frequency but increased linearly with increase in vibratory power. This phenomenon was attributed to ultrasonically facilitated formation and movement of dislocations within the crystal lattice structure, so that intercrystalline slip could take place more readily. Thus ultrasonically activated metals

*F. Blaha and B. Langenecker, "Dehnung von Zink-Kristallen unter Ultraschalleinwirkung," Die Naturwissenschaften, Vol. 42, 1955, p. 556; ibid., "Untersuchungen zur Bearbeitungserholung (Verformungsentfestigung) von Metallkristallen," Zeitschrift fur Metallkunde, Vol. 49, 1958, p. 357-360.

exhibit a type of superplasticity which is not evident in ordinary static stressing.

In addition, and particularly in dynamic metal forming processes, there is significantly reduced friction between the workpiece and the forming die, which adds an additional dimension to the ultrasonic effect. This friction-reducing effect has been demonstrated independent of the plasticity effect, as for example in the assembly of close tolerance parts or the torque tightening of threaded fasteners. This phenomenon is particularly important in dynamic forming processes such as tube and wire drawing, extrusion, and rolling, in which the workpiece makes moving contact with the forming tool.

Typical effects of ultrasonically activated forming are illustrated in Figures 1 and 2. Figure 1 shows the increased deformation obtained in the flattening of zinc wire with a roller device maintained under constant static force. The ultrasonically induced deformation was approximately twice that obtained with static force alone. In draw forming aluminum to the configuration shown in Figure 2, the use of only static force induced cracking of the metal in the area of greatest deformation. No such cracking was obtained with the superimposition of ultrasonic energy. Similar results have been obtained in the draw ironing of aluminum and brass cartridge cases, in the flange flaring of metal tubing, and in the dimpling of aircraft materials.*

Production problems in ultrasonic forming have been successfully solved with the evolution of tube drawing insatllations involving ultrasonic activation of either the draw die or the internal mandrel or both. Several such installations are routinely used in metal tubing production both in the United States and abroad. This experience is particularly signigicant since a drawbench operation was projected for the dynamic forming aspect of this program. The materials drawn span the spectrum from soft aluminum and copper to hard titanium and steel. The benefits are reflected in both reduced costs and higher quality tubing: reduced draw forces, increased area reduction per pass, increased drawing rates, elimination of stick-slip and chatter, smoother surface finish, improved dimensional control over long lengths, and increased diameter-to-wall-thickness ratios. The improved surface finish with the elimination of the stick-slip phenomenon is illustrated in the ultrasonically drawn titanium rods of Figure 3.

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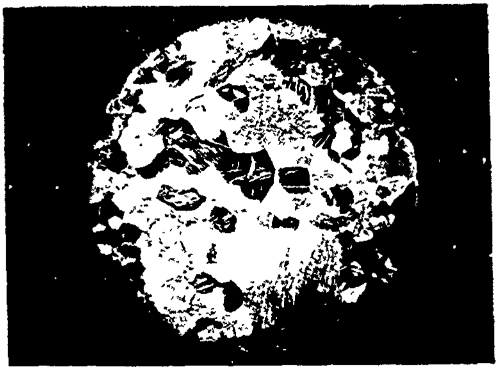
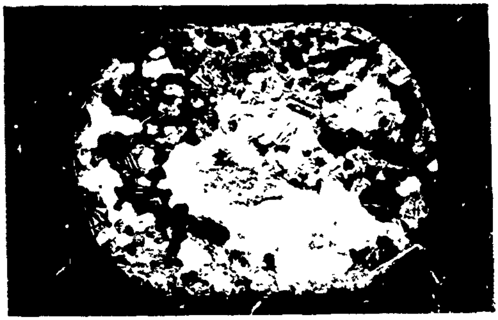
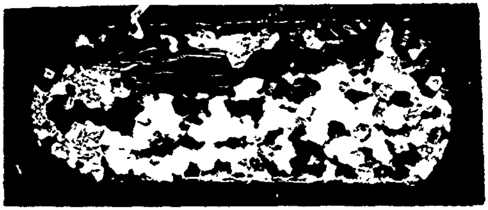
* F. R. Meyer, "Engineering Feasibility Study of Ultrasonic Applications for Aircraft Manufacture," <u>Research Report 73-15</u>, Army Contract DAAJ01-72-C-0737(P1G), Aeroprojects Incorporated, West Chester, PA, September 1973.



Cross section of wire before rolling



Rolled with 1000 pounds normal force (Thickness reduced to 0.098 inch)



Rolled with 1000 pounds normal force and ultrasonic application at 3000 watts power (Thickness reduced to 0.0625 inch)

Figure 1. Ultrasonic effect on rolling of 1/8-inch-diameter zinc wire (30X magnification).

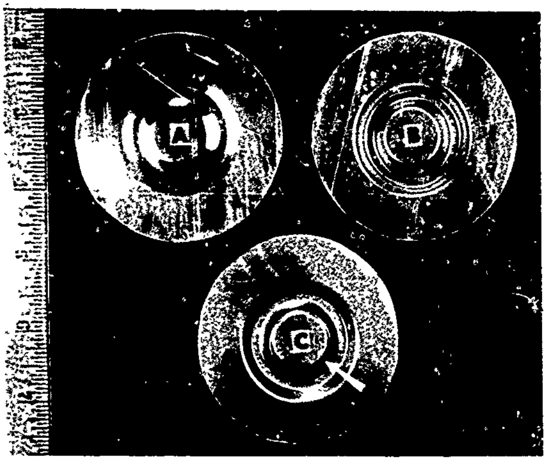


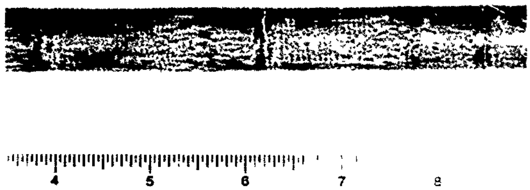
Figure 2. Aluminum sheet, 0.020 inch thick, drawn with and without ultrasonic activation.

A. Non-vibrated specimen.

B. Vibrated specimen produced with same static load as A.

C. Non-vibrated specimen drawn with sufficient static load to achieve same depth as B. (Note tear at arrow.)

Group drawn with and without ultrasonics



Drawn without ultrasonics

Drawn with ultrasonics

Figure 3. Titanium rods cold-drawn with and without ultrasonics.

The ultrasonic effect on bending of hard metal strips and panels has likewise been addressed. Several years ago,* work was done in the bending and twisting of 1-inch-wide ribbons of 304 and 17-4 PH stainless steel 0.100 inch and 0.125 inch thick. Reduction in springback of the metal was of primary interest. When the strips were bent to angles ranging from 10 to 60 degrees, ultrasonic activation increased the residual angle by 290 percent at the smallest angle to 13 percent at the largest angle. With twist angles in the range from 10 to 25 degrees, the residual twist angle increased by 10 to 100 percent with ultrasonic activation. The decreased effect at the larger angles was related to the constant ultrasonic power level used throughout the tests. No microstructural differences were found between the ultrasonically and non-ultrasonically bent samples.

More recent work** involved the drape forming of 6Al-4V titanium alloy panels 0.040 inch thick by 4 inches wide by 16 inches long. Preliminary studies with tensile stressing of metal strips and dumbbell specimens established a reduction of about 15 percent in the yield and ultimate strengths of the material with ultrasonic activation. For the panel specimens, ultrasonic energy was transmitted directly into the titanium sheet via several transducer-coupling systems braze-attached to the sheets. This arrangement was used to typify the non ultrasonic drape forming process then under consideration for this forming process. The configuration simulated the leading edge of a helicopter rotor blade. When bent with static force alone. the residual included angle was 108 degrees; with superimposed ultrasonics, the included angle was 97 degrees, approximately 10 percent improvement. With this arrangement, it was concluded that transmission of the energy into the titanium was not the most efficient approach because of the intrinsically low acoustic impedance of the sheet geometry.

Additional experiments were carried out with an ultrasonically activated punch mounted on a standard ultrasonic spot welder, using the arrangement shown at the top in Figure 4. When titanium alloy sheet 0.050 inch thick was deformed under a static force of 700 pounds, little indentation was obtained. With the same force and 2000 watts ultrasonic activation, a full 90-degree bend was obtained, and the resid-

* N. Marpois, W. H. Bayles, J. Devine, and F. R. Meyer, "Ultrasonic Application to Facilitate Straightening of Steam Turbine Blades," Research Report 70-31, Aeroprojects Incorporated, West Chester, PA, November 1970.

** H. A. Scheetz, "Ultrasonic Cold Forming of Titanium," Research Report 77-8, Sonobond Corporation, West Chester, PA, May 1977.

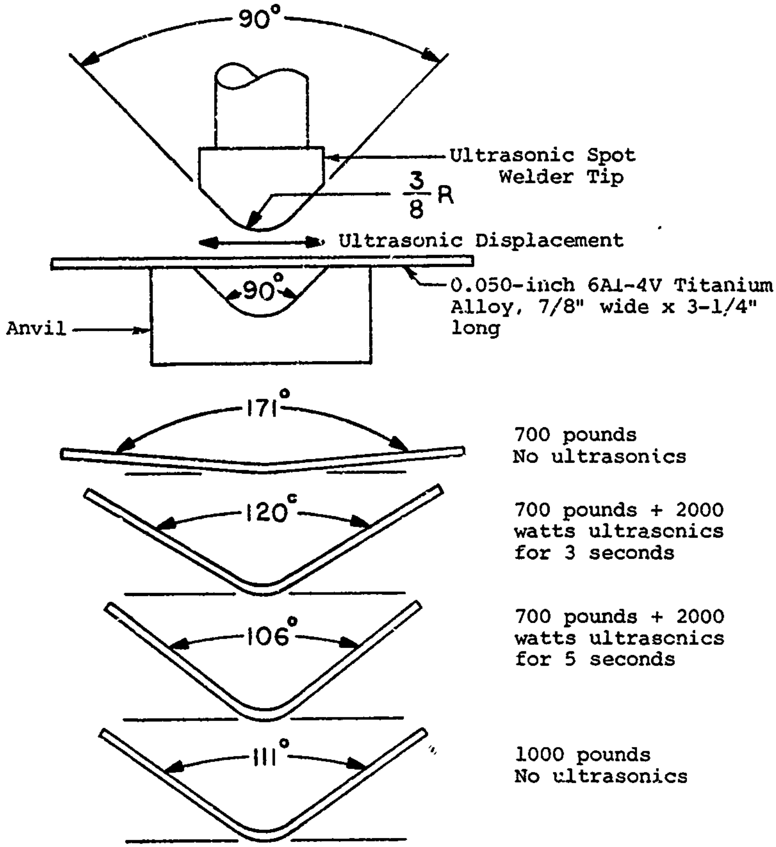


Figure 4. Cold bending of 6Al-4V titanium alloy, both statically and with ultrasonics.

ual included angle was 106 degrees. With 1000 pounds static force alone, the residual angle was 111 degrees.

Since the efforts described above, further advances have been made in the ultrasonic equipment adaptable to such forming processes and particularly in the power capabilities of such equipment. Whereas the maximum power used in the earlier work was 2000 electrical watts input to the transducer, equipment of 4000 watts capacity is now routinely used for a variety of applications, including ultrasonic spot welding. In addition, both transducers and coupling systems have been made more efficient, and the principles of acoustic transmission into forming tools have been more clearly defined.

APPROACH

As noted, the program objective was to develop and evaluate a system for utilizing ultrasonic energy to assist in forming helicopter rotor blade nosecaps to final dimensions. The selected configuration was the H-64 helicopter rotor blade which had the cross-sectional configuration shown in Figure 5.

The most critical portion of this section was the 60-degree angle at the leading edge of the profile, shown in Figure 6. This area had an outside radius of 0.168 inch. The specifications called for a maximum allowable contour deviation of $\pm$ 0.008 inch and a thickness deviation not to exceed $\pm$ 0.005 inch.

The first phase of the work involved static forming of small coupons to the required contour. Phase II would involve dynamic forming of extended lengths to this contour, using a drawbench to translate the workpiece through the forming tools. Under Phase III, a triad ultrasonic system would be used to activate a larger area of the leading edge profile in a dynamic arrangement. Such a system would cover a 4.5-inch section of the leading edge, which was the critical area for forming. The areas toward the trailing edge of the rotor blade presented no critical forming problem.

The static forming activity of Phase I was carried out with the support and cooperation of Hughes Helicopters, Culver City, California, who supplied the materials for forming and conducted evaluations of the formed parts.

The basic ultrasonic equipment was a standard 4000-watt ultrasonic spot welder which had the capability of applying static loads up to about 3000 pounds. This system was modified to meet the requirements of the forming operation, and special punch and die sets to provide the required contour were designed and fabricated.

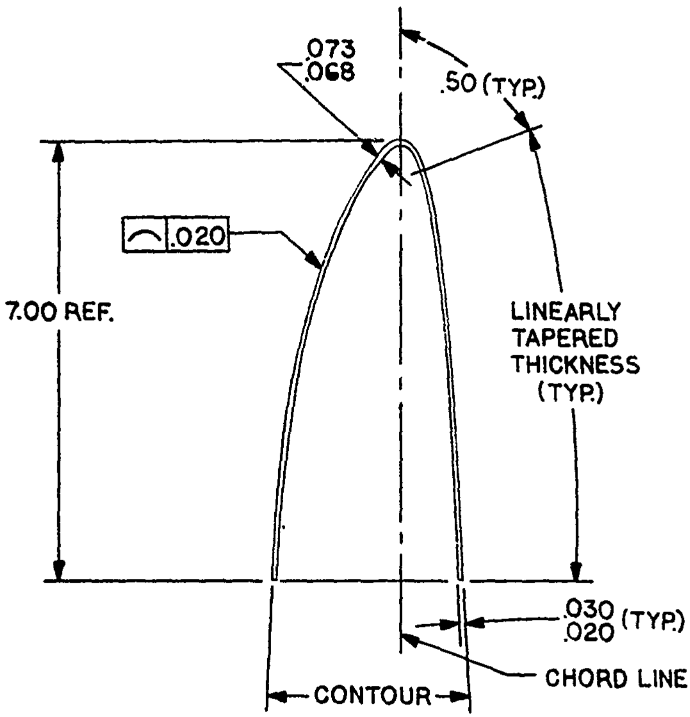


Figure 5. Cross section of helicopter rotor blade.

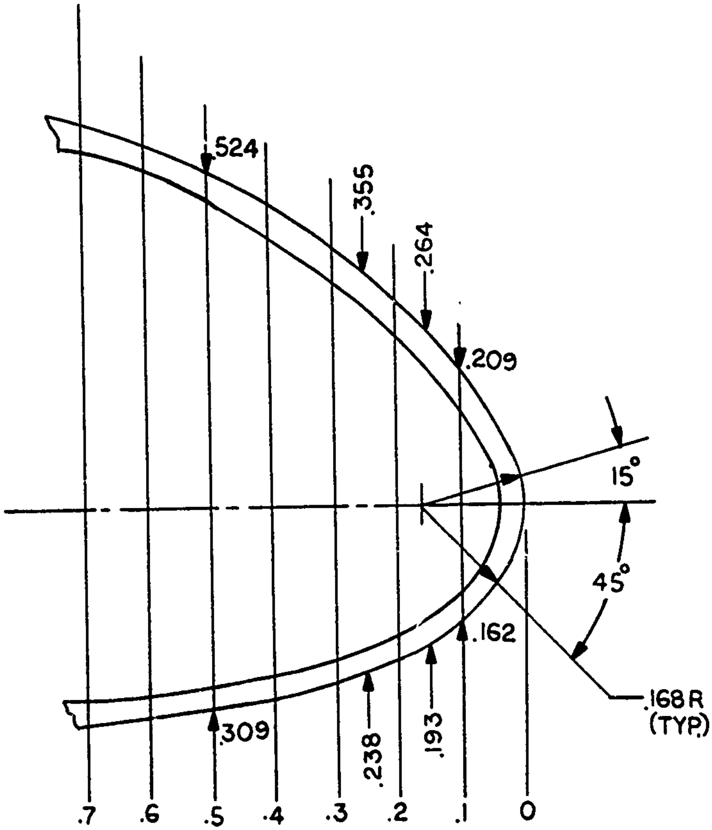


Figure 6. Main rotor blade leading edge contour.
(Scale - 5:1)

With this equipment, parameters of static force, ultrasonic power level, and dwell time were established for forming coupons of the requisite materials: nickel 200, 6Al-4V titanium alloy, and AM355-CRT stainless steel. Modifications in the equipment and procedures were made as the work progressed. Samples of the formed specimens were forwarded to Hughes Helicopters for dimensional and hardness measurements and metallographic examination.

Meanwhile consideration was given to the acquisition of a dynamic system that would be suitable for forming extended lengths of the nose section in the single or triad module arrangement. Since it appeared that this could be most effectively accomplished with a commercial type drawbench, a survey was made of drawbench manufacturers, and a unit fulfilling the required specifications was selected. The equipment assembled for the static forming of Phase I was designed for mounting on such a drawbench.

The dynamic forming phase of the investigation was suspended as a result of funding limitations and the prospect of the composite rotor blade gaining acceptance in the industry. The cold forming of titanium which was accomplished within the scope of this program offers promise to the aerospace designer for use of a process whereby ultrasonic energy can assist the cold forming of selected aerospace materials.

MATERIALS

The workpiece materials provided by Hughes Helicopters were:

1. Nickel, 6R200 Huntington Alloy

2. Titanium 6Al-4V alloy

3. Stainless steel AM355-CRT.

Basic pertinent properties of these materials in the longitudinal direction are given in Table 1.

It was originally intended that these materials be evaluated in a thickness of 0.040 inch. However, the titanium alloy and nickel were not available in this thickness, and 0.050-inch material was substituted in these materials. The steel was used in the 0.040-inch thickness. Coupons of each material were 1.5 inches wide by 2 inches long. The change in thickness after the work was initiated necessitated fabrication of additional tools, as described later.

Review of the property data in Table 1 indicates that nickel is the most readily formed of these materials because of its low yield strength and high elongation. This was verified in the experimentation. The nosecap geometry could be readily achieved even without the use of ultrasonics. On the other hand, the steel has a very high yield strength and low elongation. Early in the program it was determined that cold forming of this material in the thickness required for efficient nosecaps was somewhat beyond the capabilities of the existing ultrasonic forming equipment. Accordingly, the principal effort was directed to examination of titanium alloy 6Al-4V as the most likely candidate for the nosecaps.

TABLE 1. MATERIAL PROPERTIES

Property	Steel	Titanium	Nickel
Young's Modulus (psi)[(a)]	25.7×10^6	17.5×10^6	30.0×10^6
Yield Strength (psi)[(b)]	200,000	126,000	34,000
Tensile Strength (psi)[(b)]	220,000	140,000	61,000
Elongation (%)[(b)]	12	10	43
Hardness (Rockwell)[(c)]	47 R_c	33 R_c	47 R_b

(a) From ASM Metals Handbook

(b) Data from Hughes Helicopters

(c) Measured values

Stated properties are parallel to the rolling direction (longitudinal).

ULTRASONIC STATIC FORMING EQUIPMENT

ULTRASONIC SYSTEM

The ultrasonic equipment selected for the static forming operation consisted of a standard 4000-watt ultrasonic spot welder, which provides the basic required parameters: means for introducing ultrasonic energy through appropriately designed tools into the workpiece, a hydraulic system for static force application, and a timer to provide finite duration of the ultrasonic application. Figure 7 shows the standard welder before modification.

This equipment incorporates a wedge-reed transducer-coupling system consisting of a resonant reed and a transducer and wedge coupler perpendicular to the reed. The transducer-coupling system drives the reed in flexure, inducing lateral vibration of the forming tool located at the terminus of the reed. Static force is applied from below through the anvil and is reacted by the mass supporting the reed.

The standard transducer for this assembly (Figure 8) consisted of disks of lead zirconate titanate polarized in the thickness mode, incorporated in a rugged assembly of the tension-shell type with a bias compressive stress on the ceramic disks to preclude failure under dynamic stress. Cooling channels permitted cooling air flow through the assembly to prevent overheating and depolarization of the transducing elements. The transducer operated at a nominal frequency of 15 kilohertz and had a maximum power capacity of 4200 watts with continuous duty service.

The standard acoustic assembly was modified for forming, particularly to incorporate a force-insensitive mount to provide optimum efficiency of energy transmission under the static loads. This device makes it possible to mount a transmission system rigidly without appreciable loss of acoustic energy to the supporting structure, without appreciably changing the resonant frequency of the system, and without mounting-induced impedance changes. The force-insensitive mount is a tuned member, often a sleeve, metallurgically attached to the transmitting coupler and axially resonant. One end is affixed to the coupler and the other end is free. The high impedance of the sleeve in the air results in negligible energy transmission through it, practically complete wave reflection, and a true standing wave pattern in the sleeve so that there is a pre-established non-shifting nodal point one-quarter wavelength from the end. Here, in contrast to elastomeric mounting, a rigid mounting flange can be affixed with minimal loss of energy even though very high axial loads are applied. This force-

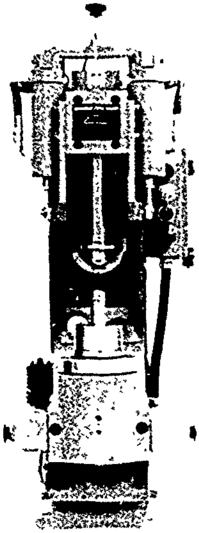


Figure 7. Standard 4000-watt ultrasonic spot welder.

Figure 8. Piezoelectric tension-shell transducer with 4000 watts_power rating.

insensitive mount was installed on the transducer-wedge assembly as shown in Figure 9.

In addition, a new anvil (Figure 10) was designed so that it would provide for taperlock attachment of the forming tool. The reed is standardly designed to accept a taperlock tool.

A primary consideration in assembling the ultrasonic system was to provide equipment that would be adaptable to dynamic processing of the nosecap materials on a drawbench. Figure 11 shows the complete system with one set of forming tools installed.

The frequency converter used to provide the high-frequency electrical power to drive the transducer was a hybrid junction transistorized solid-state device consisting of an amplifier and oscillators (Figure 12). The output frequency of the system could be fine-tuned to precisely match the operating frequency of the transducer-coupling system. The frequency was ultra-stable (± 1 percent) to ensure repeatability. The unit was triple-protected for line current, RF power overload, and thermal overheat. Cooling fans provided forced circulation of air through the system.

Specifications of the ultrasonic equipment are summarized in Table 2.

TOOLING

The tools designed and fabricated specifically for forming the specimens consisted of punches and dies contoured to the required geometry. Several sets of tools were fabricated as dictated by the anticipated and changing requirements of the program.

The first set, shown in Figure 13, consisted of a punch and dies for producing a bend with the required 0.168-inch radius and 60-degree included angle. Initially a die was made to accommodate sheet material 0.040-inch thick. When the 0.040-inch material was not available in the nickel and titanium alloy, additional dies were made to accommodate the 0.050-inch thickness.

A second set of tools, Figure 14, provided for an included angle of 45 degrees in order to allow for springback that could occur with the higher yield strength materials. Dies were made to accommodate 0.040-inch and 0.050-inch material.

When work was initiated with the titanium alloy, it was found that this material cracked with non-ultrasonic

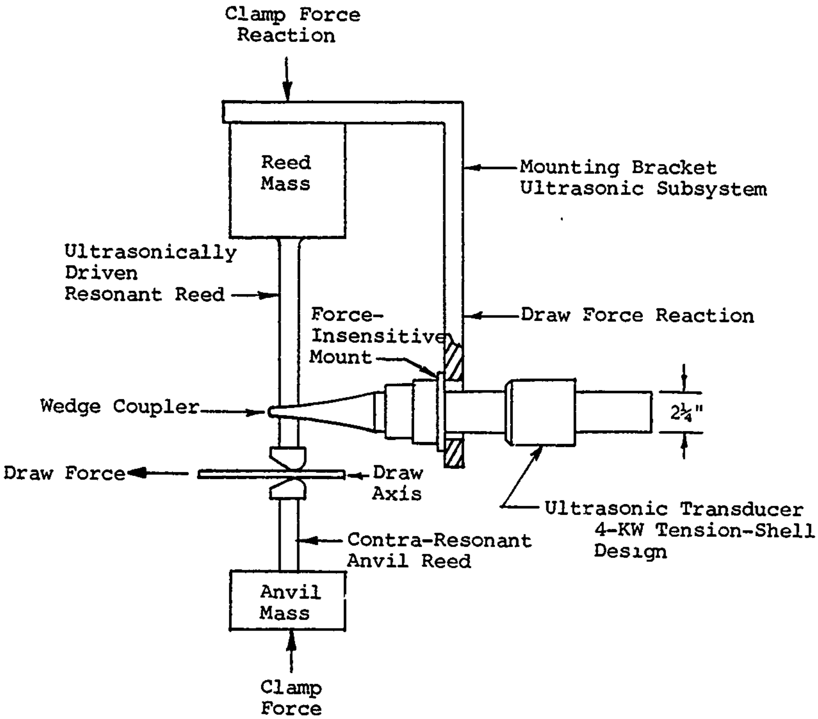


Figure 9. Side view of single ultrasonic subsystem.

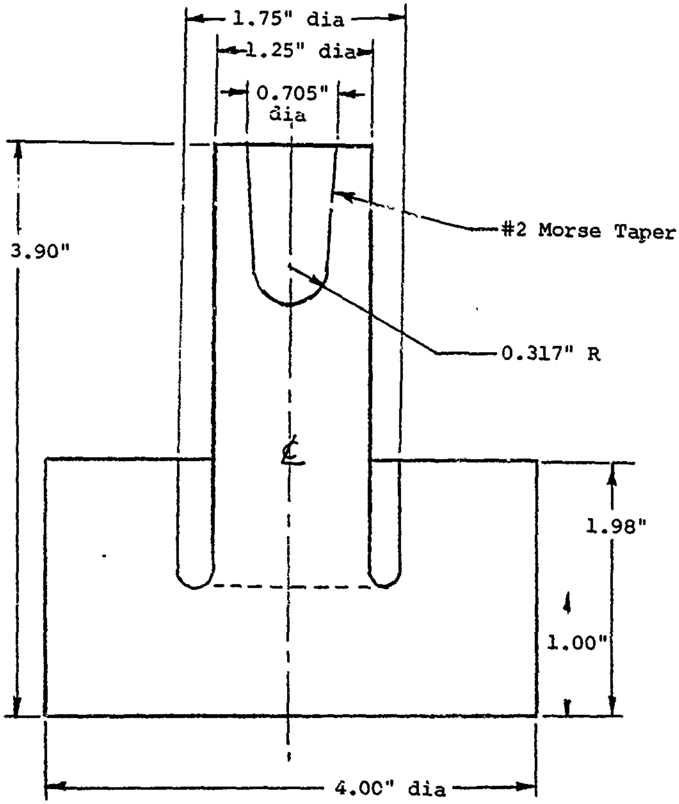


Figure 10. Anvil modified for ultrasonic forming system.

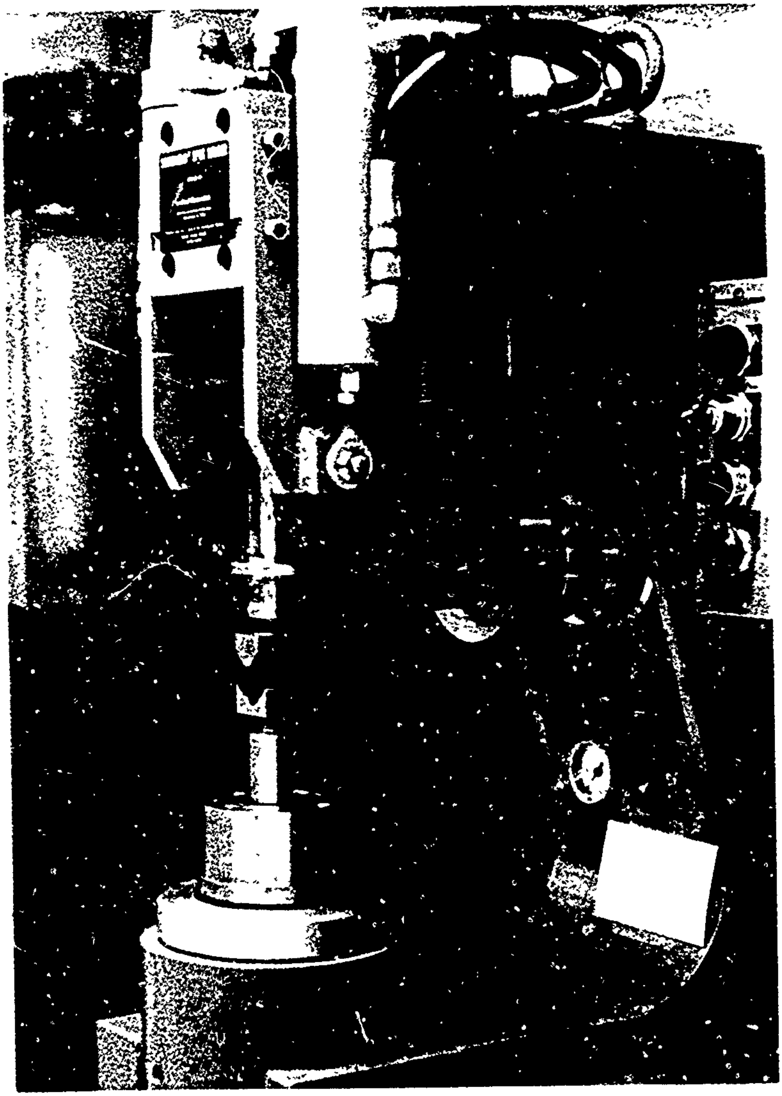


Figure 11. Ultrasonic machine modified for forming operations.

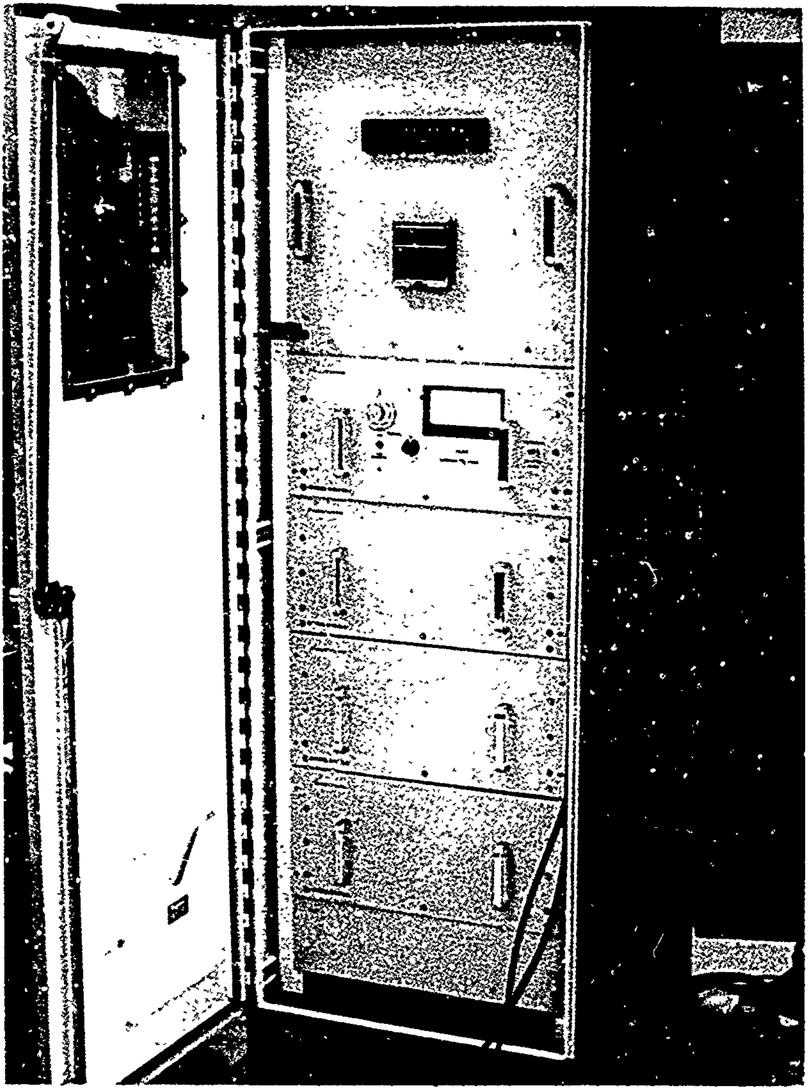


Figure 12. 4000-Watt ultrasonic frequency converter (with front door open).

TABLE 2. ULTRASONIC EQUIPMENT SPECIFICATIONS

TRANSDUCER

Type: Piezoelectric ceramic, tension-shell design.

Frequency: 15 kilohertz nominal.

Power Capacity: 4.2 kilowatts continuous duty.

Cooling Air Requirement: 60 psi of clean, dry air (2^{o} dew point) at 2 scfm

Size: 17 inches long by 4.5 inches maximum diameter.

Weight: 40 pounds.

FREQUENCY CONVERTER

Input Power Requirement: 480 volts, 50/60 hertz, three-phase, 30 amperes.

Frequency: 15 kilohertz nominal.

Output Power: 4.2 kilowatts maximum into matched resistive load; continuously variable from 300 to 4200 watts.

Cabinet Size: 30 inches wide x 75 inches high x 27 inches deep.

Weight: 800 pounds.

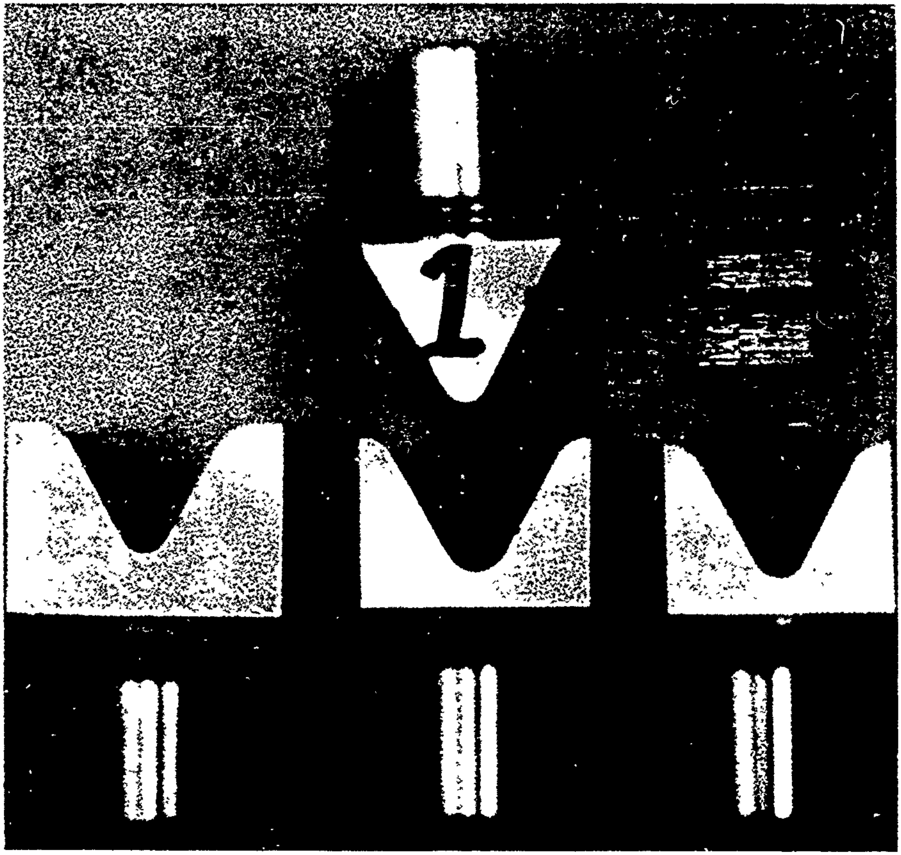


Figure 13. Punch and die set for bending to 60-degree angle and 0.168-inch radius. Dies accommodate 0.040-inch and 0.050-inch sheet thickness.

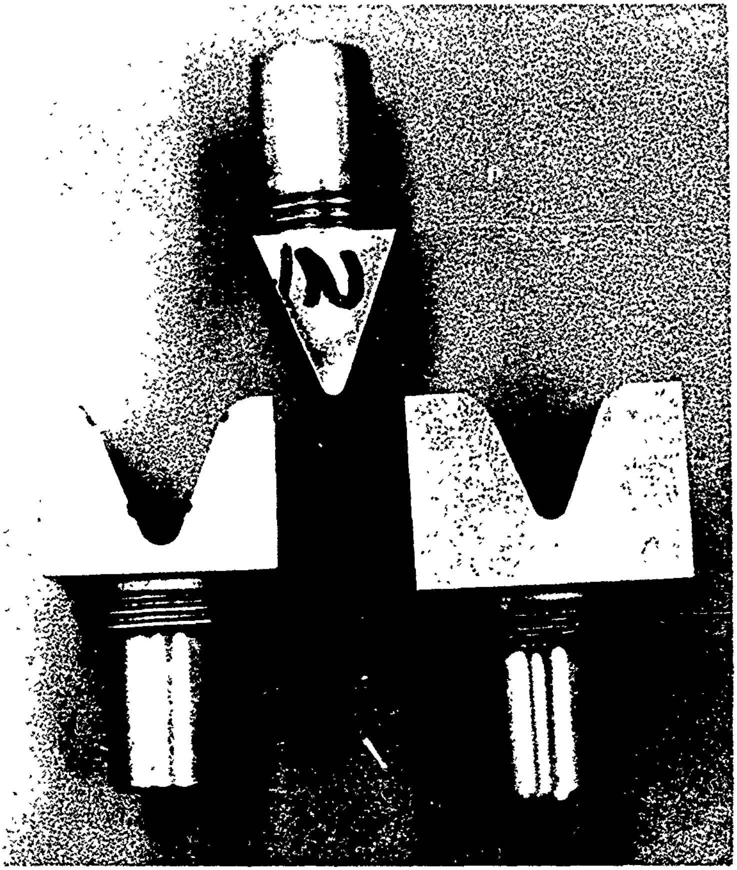


Figure 14. Punch and die set for 45-degree angle bend.

forming (although not with ultrasonic forming), and it was decided to use two-step forming to accomplish the required bend. A third set of tools was therefore made for the intermediate forming step. These tools, Figure 15, provided for a radius of 0.375 inch and an included angle of 90 degrees.

The tools were fabricated from H13 tool steel. All punches were designed with a #2 Morse taperlock attachment to the reed in the ultrasonic system. All dies were likewise designed for taperlock attachment to the anvil. Figure 11 shows one set of tools installed on the machine.

After fabrication and assembly, the equipment and tooling were checked out by forming coupons of aluminum alloy to the stated geometry. Satisfactory operation was established.

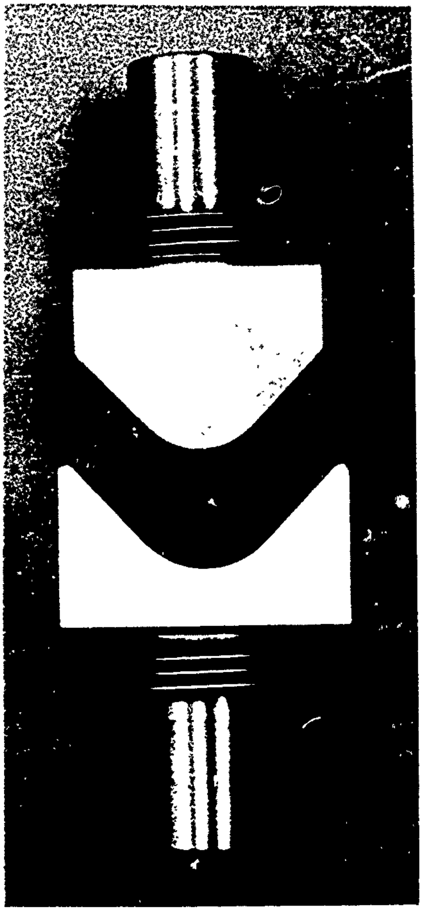


Figure 15. Intermediate tooling for 90-degree angle bend with 0.375-inch radius.

EXPERIMENTAL INVESTIGATIONS

PRELIMINARY EXPERIMENTS

Using the equipment and tooling previously described, bending tests were conducted on 1.5 by 2.0 inch specimens of the 0.050-inch thick nickel 200. Both 45-degree and 60-degree angle tools were used. Bending parameters were varied from 800 to 3600 pounds static force, 0 to 3000 watts ultrasonic power, and a dwell time of 1 second. Because of the low yield strength of the nickel (34,000 psi), well-formed parts without springback were readily obtained both with and without ultrasonic application.

The steel AM355-CRT, 0.040 inch thick, proved to be much more difficult to form because of its high yield strength (200,000 psi). Bends of 45 and 60 degrees were made with 3600 pounds of static force, 2000 to 3000 watts power, and 1 to 3 seconds dwell time, and with the tools oriented both parallel and perpendicular to the transducer axis. Substantial springback (5 to 10 degrees) occurred both with and without ultrasonic application. The combined static and ultrasonic dynamic forces apparently were not sufficient to exceed the yield strength of the steel.

The titanium 6Al-4V alloy, with an intermediate yield strength of 126,000 psi, presented a different problem. Without ultrasonic application and with a static force of about 2700 pounds, the material could not be formed to either 45 or 60 degree angles. The specimens invariably cracked into two pieces along the apex of the nose. The bend radius was apparently too sharp. No such cracking occurred when ultrasonics was applied during forming.

In an effort to determine the limits of forming the titanium without ultransonics, the stroke of the punch was limited, to produce a larger included angle. Table 3 shows the results obtained with both ultrasonic and non-ultrasonic forming. All specimens were preformed without ultrasonics to about a 125-degree angle (see Specimen T4). As noted in the table, attempts to form beyond the T4 angle without ultrasonics invariably caused cracks (Specimens T6 through T9), even when the forming was done in steps. For specimens T1, T2, T3, and T5, the ultrasonics was initiated at the instant the ram punch contacted the material, and a single stroke was used to seat the punch in the die. Under these conditions, well-formed parts were obtained without cracks. Thus, with the titanium alloy, unlike the nickel or steel, ultrasonics obviously exerted a beneficial effect.

The behavior of the titanium alloy without ultrasonics triggered the decision to fabricate tools for two-step forming.

TABLE 3. PRELIMINARY BENDING OF TITANIUM SPECIMENS

Tooling: 60° Punch with 0.188-Inch Radius

Specimen No.	Static Force (lbs)	Ultrasonic Power (watts)	Dwell Time (sec)	Included Angle (degrees)	Inside Radius* (inch)	Comments
T1	2700	1400	1.0	70.0	0.109	
T2	2700	1400	1.0	69.0	0.109	
T3	2700	2200	1.0	70.5	0.109	
T4	2700	0	0	125.2	0.125	Preform
T5	2700	1400	1.0	72.0	0.109	
T6	2700	0	0	119.5	0.078	Cracked
T7	2700	0	0	99.0	0.109	Cracked
T8	2700	0	0	110.0	0.078	Cracked
T9	2700	0	0	168.0	0.093	Cracked

* To nearest 0.016 inch.

The intermediate tools (Figure 15) had an included angle of 90 degrees and a punch radius of 0.375 inch. With the two-step process, non-ultrasonic bending of the material was readily achieved.

PREPARATION OF EVALUATION SAMPLES

Evaluation samples of all three materials were prepared using the two-step process in which the coupons were bent first to a 90-degree included angle and subsequently to either 45 or 60 degrees. The selected parameters were 2400 pounds static force, 4000 watts ultrasonic power, and usually 1 second dwell time. A dwell time of 0.5 second was used in the preforming of the nickel specimens. Non-ultrasonic samples were also made using only 2400 pounds static force.

The numbers of each type of sample prepared were as follows:

Material	Included Angle	No. of Samples Ultrasonic	No. of Samples Non-Ultrasonic
Nickel	60°	25	3
	45°	5	2
Steel	60°	24	3
	45°	5	2
Titanium	60°	23	3
	90°	2	5

The included angles between the legs of all samples were measured, with the results shown in Table 4. As previously observed, there was little difference between the ultrasonic and non-ultrasonic samples of nickel. Essentially no spring-back occurred in either case. In the steel, the springback was in the range of 4 to 6 degrees for the 60-degree specimens and in the range of 3 to 4.5 degrees for the 45-degree specimens. The ultrasonic specimens exhibited about 2 percent less springback than those formed with static force alone. For the titanium alloy formed to 60 degrees, the springback ranged from 0.5 to 2.8 degrees for the ultrasonic and from 2.5 to 3 degrees for the non-ultrasonic specimens.

Nose radii were also measured to the nearest 1/64 inch. For the 60-degree angle bends, the radii ranged from 3/32 to 7/64 inch for the nickel, from 7/64 to 1/8 inch for the steel, and were uniformly 7/64 inch for the titanium. No significant difference between ultrasonic and non-ultrasonic specimens was evident.

The specimens were well-formed and clean in the nose area, and no cracks were visually observed in any of the

TABLE 4. INCLUDED ANGLES OF EVALUATION SAMPLES

Material	Included Angle (degrees)	Ultrasonic Power (watts)	Individual Included Angles (degrees)	Average (degrees)
Nickel	60	4000	60, 61, 61, 61, 60.5, 60.2, 61, 61, 61, 60.5, 60, 60.5, 61.1, 61, 60, 60.5, 60.5, 60.2, 60.5, 61, 60, 60.4, 60, 60, 60, 60.1	60.5
	60	0	59.9, 61, 61	60.6
	45	4000	44.1, 44.9, 45, 44, 45	44.6
	45	0	45.2, 45	45.1
Steel	60	4000	64, 64.2, 65, 65, 65, 64.5, 65, 65, 65, 65, 65, 63.5, 64.5, 64.5, 64.5, 65, 63.5, 66, 66, 66, 64.4, 64.5, 64, 65	64.8
	60	0	66, 66, 66	66.0
	45	4000	43.9, 43.2, 43, 43.5, 43	43.3
	45	0	44.4, 44	44.2
Titanium	90	4000	112, 112	112.0
	90	0	113.8, 113.2, 113.8, 114.3, 113.2	113.7
	60	4000	60.5, 61.5, 61.3, 61, 61, 61.5, 61.2, 61.5, 62, 62.5, 62.8, 61, 62, 61.5, 62, 62, 62, 61, 61.8, 61, 61.6, 61, 61.8	61.6
	60	0	62.5, 62.8, 63	62.8

specimens. It should be noted that no lubricant was used during forming, and there was occasional die pickup from the sheet materials being formed. The punch and die were not cleaned or polished between specimens, and the die pickup resulted in scuff marks and burn spots on some specimens. However, these imperfections always occurred on the outer legs at some distance from the nose. The critical nose area was always clean and smooth. Such die pickup would not be a problem in dynamic forming where a lubricant would be used during a drawbench operation.

HUGHES EVALUATION OF SAMPLES

Samples of 60-degree angle bends in all three materials were sent to Hughes Helicopters for evaluation of dimensional variations, surface finish, and metallurgical changes. For each material, ten ultrasonic samples and three non-ultrasonic samples were evaluated. Comparisons were made with specimens prepared by Hughes and bent to a 90-degree angle using an air-forming process.

The results of the dimensional measurements are provided in Tables 5 and 6. The included angle measurements (Table 5) are approximately the same as those recorded in Table 4 for the Sonobond measurements, and all materials showed the same advantage of ultrasonic over statically formed specimens in terms of reduced springback.

Measurements of nose radii by Hughes (Table 6) were more precise than those conducted by Sonobond. The results show that the nose radii formed under ultrasonic activation were sharper than those obtained with static force alone.

With regard to surface finish on the specimens, Hughes concentrated its attention on the scuffs and burn marks previously described. These were particularly severe on the stainless steel, where it was noted that the inside surface of the specimens showed both shallow and severe deep burnt pits, areas surrounding the pits showed discoloration ranging from straw yellow to blue, and the outside surfaces opposite the deep pits showed straw yellow discoloration. It was further noted that the pits occurred at distances ranging from 0.48 to 0.80 inch from the nose of the specimen (see Table 7). The pits ranged in size from 0.03 by 0.17 inch to 0.042 by 0.005 inch. Similar marks were observed on the titanium alloy specimens and, to a much lesser extent, on the nickel specimens, although measurements such as those in Table 7 were not made on these two materials.

In contrast, the Hughes specimens air-formed to 90 degrees showed no burnt pits and only slight surface scuffing

TABLE 5. INCLUDED ANGLE BETWEEN LEGS
(Measurements by Hughes)

Goal: 60.0° Ultrasonic, 90° Air Formed)

Material	Forming Process	Individual Angles (degrees)	Average (degrees)	Standard Deviation (degrees)
Steel	Sonobond Non-Ultrasonic	65.4, 66.0, 66.3	65.9	0.5
	Sonobond Ultrasonic	64.8, 64.6, 64.9, 64.5, 64.6, 64, 64.7, 64.9, 65, 65	64.7	0.3
	Hughes Air Formed	90.5, 90, 91, 90, 90, 90, 91, 91, 90.5, 90.5	90.5	0.44
Titanium	Sonobond Non-Ultrasonic	63, 63.3, 63.5	63.3	0.3
	Sonobond Ultrasonic	62.3, 63, 61.6, 61.6, 61.2, 62, 61, 62.4, 61, 62	61.8	0.7
	Hughes Air Formed	91.5, 91, 91, 90.5, 90, 90, 90, 90, 90, 90	90.4	0.57
Nickel	Sonobond Non-Ultrasonic	60, 61.3, 61.3	60.9	0.8
	Sonobond Ultrasonic	60.4, 60.2, 60.3 60.3, 61, 60.9, 61, 60.1, 60.5, 61	60.6	0.4
	Hughes Air Formed	92, 91.5, 90.5, 90.5, 90.5, 87.5, 89.5, 90, 90	90.2	1.2

TABLE 6. HUGHES MEASUREMENTS OF NOSE RADII

Goal: 0.168 inch

Material	Forming Process	Individual Radii (inch)	Average (inch)	Standard Deviation (inch)
Steel	Sonobond Non-Ultrasonic	0.152, 0.152 0.152	0.152	0
	Sonobond Ultrasonic	0.145, 0.145, 0.145, 0.145, 0.145, 0.145, 0.145, 0.146, 0.145, 0.145	0.145	0
	Hughes Air Formed	0.168, 0.167, 0.164, 0.169, 0.164, 0.162, 0.166, 0.164 0.166, 0.164	0.165	0.002
Titanium	Sonobond Non-Ultrasonic	0.153, 0.155, 0.153	0.154	
	Sonobond Ultrasonic	0.154, 0.153, 0.155, 0.150, 0.154, 0.154, 0.153, 0.155, 0.152, 0.154	0.153	0.005
	Hughes Air Formed	0.174, 0.178, 0.160, 0.180, 0.175, 0.173, 0.176, 0.174, 0.172, 0.179	0.174	0.002
Nickel	Sonobond Non-Ultrasonic	0.152, 0.152 0.152	0.152	0
	Sonobond Ultrasonic	0.143, 0.147, 0.144, 0.147, 0.144, 0.142, 0.139, 0.139, 0.144, 0.145	0.143	0.003
	Hughes Air Formed	0.163, 0.162, 0.156, 0.161, 0.159, 0.164, 0.161, 0.159, 0.160, 0.160	0.161	0.002

TABLE 7. BURNT PIT DISTRIBUTION OF STAINLESS STEEL

Sample No.	Pit Distance from Nose	No. of Pits*	Pit Size Range (inches)	No. of Spots	Discoloration**
S1	0.57 - 0.75	12	0.030 x 0.040 - 0.030 x 0.185		Faint
S2	0.55 - 0.65	9	0.03 [illegible] 035 - 0.07 [illegible] .6	4	Straw yellow, distinctive
S3	0.58 - 0.80	8	0.04 x 0.055 - 0.08 x 0.125	3	Straw yellow
S4	0.53 - 0.75	9	0.040 x 0.045 - 0.07 x 0.150	2	Straw yellow
S5	0.54 - 0.62	9	0.032 x 0.030 - 0.07 x 0.140	4	Straw yellow
S6	0.57 - 0.76	9	0.030 x 0.040 - 0.06 x 0.150	4	Straw yellow
S7	0.58 - 0.71	10	0.025 x 0.035 - 0.06 x 0.130	5	Straw yellow
S8	0.48 - 0.75	10	0.020 x 0.025 - 0.09 x 0.170	5	Straw yellow
S9	0.54 - 0.63	16	0.023 x 0.030 - 0.07 x 0.110	0	Straw yellow
S10	0.58 - 0.73	14	0.025 x 0.030 - 0.03 x 0.16	0	Straw yellow

* Pits on inside surface.

** Discoloration on outside surface opposite pits.

at an area 1/4 inch from the nose.

Likewise the metallurgical examination by Hughes was concentrated on the burnt pits and not on the nose section of primary interest. Samples showing the burnt pits were mounted in bakelite and cross-sectioned for metallurgical examination. The hardness in the vicinity of the pit was determined by microhardness measurements, and hairline cracks along the periphery of the pits were examined by a Scanning Electron Microscopic (SEM) method.

It was noted that the ultrasonically formed stainless steel and titanium alloy showed cracks, structural changes, and changed mechanical properties. Tables 8-10 present the results of these evaluations. In the stainless steel specimens, photomicrographs in the vicinity of the pit showed a white zone which was interpreted as austenite, converted from martensite and retained austenite. The titanium alloy showed no apparent structural change, but the hardness readings indicated some anomaly. Nickel showed little change in structure and hardness in the vicinity of the pits.

It should be emphasized that these surface finish and metallurgical examinations performed by Hughes were conducted only on the pitted areas on the legs of the specimens, remote from the nose areas. No such evaluation was made of the nose areas themselves, which were of primary importance in this investigation. As previously noted, the imperfections were due to die and punch pickup from the materials being formed, and such pickup would not occur with a dynamic lubricated process for forming the nosecap sections. Consequently these Hughes observations were not germane to the ultimate objectives of the program.

PREPARATION AND EVALUATION OF ADDITIONAL TITANIUM SAMPLES

Subsequent to the evaluations reported by Hughes Helicopters, additional formed samples of the titanium alloy were prepared and forwarded to Hughes.

These samples were preformed to the 90-degree bend with and without ultrasonic application and were subsequently formed to 60 degrees. Parameters were the same as previously used, except that the ultrasonic power level was reduced to 2000 watts. In an effort to eliminate the scuff marks and pitting which were of such concern to Hughes, for some of these specimens a thin Teflon rubber film was inserted between the specimens and the die during forming. This provided the desired protection, and such samples were essentially free from the imperfections that characterized the earlier samples.

TABLE 8. HARDNESS NEAR PIT AREA, ULTRASONICALLY FORMED STEEL

Distance from Bottom of Pit (inch)	Hardness (R_c)	Comments
0.002	34.7	Retained austenite (white zone)
0.004	38.2	Retained austenite
0.006	40.8	Heat-affected zone
0.008	41.3	Heat-affected zone
0.010	43.7	Heat-affected zone
0.012	46.4	Heat-affected zone
0.014	46.4	Heat-affected zone
0.016	45.0	Heat-affected zone
0.018	45.3	Heat-affected zone
0.022	43.7	Heat-affected zone
0.026	46.4	Heat-affected zone
Away from Pit Core	46.1) 46.1) 46.9) Av. 46.4	Martensite and Retained austenite
Dimensions of Pit	Depth 0.007 inch Length 0.050 inch, maximum	

TABLE 9. HARDNESS NEAR PIT AREA, ULTRASONICALLY FORMED TITANIUM

Distance from Bottom of Pit (inch)	Hardness (R_C)	Comments
0.002	33.5	Alpha and Beta
0.004	36.3	Alpha and Beta
0.006	34.1	Alpha and Beta
0.008	34.9	Alpha and Beta
0.010	37.1	Alpha and Beta
0.012	34.4	Alpha and Beta
0.014	33.5	Alpha and Beta
0.016	34.1	Alpha and Beta
0.018	34.7	Alpha and Beta
0.020	36.6	Alpha and Beta
0.022	37.4	Alpha and Beta
0.024	34.7	Alpha and Beta
0.026	37.1	Alpha and Beta
Away from Pit Core	33.5) 36.1) Av. 34.8 34.7)	
Dimensions of Pit	Depth 0.006 inch Length 0.043 inch, maximum	

TABLE 10. HARDNESS NEAR PIT AREA, ULTRASONICALLY FORMED NICKEL

Distance from Bottom of Pit (inch)	Hardness (R_b)	Comments
0.002	63.8	No microstructural change
0.006	71.1	No microstructural change
0.010	70.1	No microstructural change
0.014	65.5	No microstructural change
0.018	66.3	No microstructural change
0.022	65.5	No microstructural change
0.026	67.3	No microstructural change
Away from Pit Core	65.5) 67.3) Av. 68.3 72.1)	
Dimensions of Pit	Depth 0.005 inch Length 0.045 inch, maximum	

The results of the Hughes evaluation of these additional samples are provided in Table 11.

TABLE 11. ADDITIONAL SAMPLES OF TITANIUM 6Al-4V ALLOY EXAMINED

All samples preformed to 90 degrees and subsequently formed to 60 degrees.

Sample No.	No. of Pieces	Process	Results
1	3	Non-ultrasonic to 90°.	Outside surface scuffed slightly.
2	7	Non-ultrasonic to 90°, then ultrasonic to 60°.	Outside surface scuffed. One piece broke into halves. Two pieces cracked over entire nose area. Three pieces had small cracks and orange peel. Included angle 63.5°.
3	2	Ultrasonically preformed to 90°.	Outside surface scuffed slightly.
4	6	Preformed to 90°, then ultrasonically formed to 60°, 2000 watts, 2400 lbs, 1 sec dwell.	Burnt pit shallower than before on inside surface. Tiny cracks. Included angles 61-64°, nose radius 0.145".
5	1	Preformed to 90°, then ultrasonically formed to 60°, 2000 watts, 2400 lbs, 1 sec dwell. Used thin Teflon rubber film between titanium and die.	Numerous small nose cracks. No scuff marks. Nose radius 0.150".
6	2	Same as above.	Outside surface scuff marks barely visible. Included angle 78.2°. Nose radius 0.148".
7	2	Same as above.	Outside surface scuff marks barely visible. Burnt pit and cracks near nose, inside surface. Included angle 78.3°. Nose radii 0.150", 0.151".

ULTRASONIC DYNAMIC FORMING EQUIPMENT

The experimentation previously described was oriented to static forming of small coupons of the materials of interest. The ultimate objective of the program was a dynamic system that would form extended lengths of the materials to the required nosecap contour.

For this purpose, it was decided to use an ultrasonically activated drawbench, sinch ultrasonic tube drawing had proven to be eminently effective for production applications. The nosecap forming would not be significantly different from tube drawing except that the final configuration would be open rather than a closed tube. An ultrasonic system such as that designed for static forming (Figure 9) could be mounted on the drawbench, and the material to be formed could be drawn through the punch and die set. As previously noted, the materials of interest, and particularly the titanium alloy, could be ultrasonically drawn in a single-step process to the required configuration.

With this arrangement in mind, drawbench specifications, delineated in Table 12, were forwarded to a number of drawbench manufacturers to determine if they could provide a drawbench suitable for this application. Specific interest was expressed by three drawbench manufacturers:

1. All American Engineering Company
   Box 1247
   801 South Madison Street
   Wilmington, Delaware 19899

2. The Fenn Manufacturing Company
   200 Fenn Road
   Newington, Connecticut 06110

3. Witloe Associates, Inc.
   Noble Road
   Atglen, Pennsylvania 19310

These firms were investigated by personal visits to their facilities and appraisal of their capabilities.

All American Industries had only a basic knowledge of drawbenches and did not display the proficiency necessary to produce the required drawbench. Their method of gripping was unsatisfactory, since they intended to drill a hole in the draw material, place a bar through the hole, and pull the bar. This would induce indeterminable stress on the draw material which could eventually lead to fracture. This and other factors led to the rejection of this source for the drawbench.

TABLE 12. SPECIFICATION FOR AN ULTRASONIC DRAWBENCH

1. Purpose. This requirement is based on the need for a means to cold-form materials in the shape of a helicopter rotor blade nosecap. The specific requirement is for the nosecap on the Hughes AH-64 Armed Attack Helicopter.

2. Materials. The materials to be drawn include:

   a. Titanium 6Al-4V Alloy
   b. Nickel
   c. AM355-CRT Stainless Steel.

3. Dimensions. The preforms are a maximum of 28 feet in length to a minimum of 6 feet in length; material thickness 0.050 inch; the preform is 12 inches on the arc. Note: Sufficient material must be provided at the drawing end to accommodate drawing grips.

   A 5-foot tooling area to accommodate the ultrasonic head must be provided. Sonobond will supply mounting details for the ultrasonically activated dies.

4. Feed. Ball screw feed is required at a maximum of 8 feet per minute; smooth linear feed is required.

5. Draw Force. The bench must be designed for a maximum draw force of 20,000 pounds. Frame must be capable of withstanding all draw forces.

6. Lubrication. Automatic lubrication ahead of the ultrasonic dies is required.

7. Clearance. The ultrasonic anvil will fit inside the nosecap and since the anvil will be mounted on the drawbench, sufficient clearance must be provided to avoid interference with the preform as it moves along the drawbench. A schematic of the side view of the ultrasonic head is provided.

8. Power. Sufficient power of a suitable source must be provided to generate the draw force as indicated above.

9. Interlock. Drawbench controls must be interlocked with the ultrasonic controls such that movement of the preform through the ultrasonic dies is accompanied by ultrasonic activation.

Witloe Associates had never built a drawbench but had rebuilt and repaired machinery including drawbenches. It was felt that the requirements for rebuilding may be more stringent than building a system from the outset, since new components must be assembled to existing parts. Witloe proposed to use a caliper jaw to grip the specimen to be drawn.

Fenn Manufacturing Company had a first-class machine fabrication facility, had fabricated drawbenches, and appeared to be qualified to produce the required equipment. They were not familiar with titanium and were not sure how they would grip it for the draw. They also did not indicate how they would support the draw screw. Eventually they submitted the specifications provided in Table 13, which appeared to fulfill the requirements for ultrasonic dynamic forming. This facility was therefore selected to provide the required drawbench.

Since this program was suspended before the dynamic forming phase could be undertaken, no further action was taken on procurement and assembly of the dynamic system.

TABLE 13. SPECIFICATIONS FOR 20,000-POUND BALL SCREW DRAWBENCH COMPLETE WITH ACCESSORIES

Prepared by The Fenn Manufacturing Company, Newington, Connecticut

GENERAL DATA

Type of Equipment	Drawbench - Ball Screw Type
Speed	1 to 8 feet per minute
Maximum Entry Size	6-inch Diameter Tube
Materials	Titanium, Nickel, and Stainless Steel
Maximum Speed - Pusher	8 feet per minute
Minimum Speed - Pusher	1 foot per minute
Maximum Speed - Puller	8 feet per minute
Minimum Speed - Puller	1 foot per minute
Minimum Preform Length	6 feet
Maximum Preform Length	28 feet
Maximum Draw	30 feet
Draw Pull (Maximum)	20,000 pounds.

DESCRIPTION OF EQUIPMENT

ITEM 1

One (1) 20,000-pound Pull Drawbench utilizing a ball screw arrangement to obtain a smooth linear pull. The frame of this unit is made of rigid heavy-duty boiler plate. The puller is mounted on precision roller bearings so as to form a trolley. The trolley is contained between retaining gibs and the frame unit which has a minimum running clearance. This assures good uniform action in the ball and screw assembly.

A 5-foot space is provided in the center of the bench, and in the event of an order, Sonobond will provide Fenn with mounting details for the ultrasonic die unit. The movable gripper jaw unit will be provided with one (1) set of jaws to customer's requirements.

TABLE 13 (Concluded)

An automatic jaw-opening actuator is provided on the pulling side of the bench and is adjustable along its length to accommodate varying lengths of after-forms. When the end of the preform passes through the die, a pair of rollers on the gripper unit strikes the actuator and opens the gripper jaws, allowing the after-form to be removed.

ITEM 2

One (1) 20,000-pound Push Form Unit is on a plate which can be relocated into several locations (several sets of holes will be provided for this purpose). A plate will be provided with preform shape in it. With this unit the forming dies can be in their working position while the preform is pushed through sufficiently so it can be picked up by the gripper on the other side of the die. The maximum push stroke will be 3 feet.

ITEM 3

Variable Speed Drive Units for both the pusher and puller will give a speed range of 1 to 8 feet per minute in both the forward and reverse directions. Both the puller ball screw and the pusher ball screw are driven separately by their own drive motor. There will be one power unit supplying both drive motors so only one can be run at any one time.

CONCLUSIONS AND RECOMMENDATIONS

1. The forming of titanium alloy can definitely be benefited with ultrasonic application. Ultrasonic forming to the required 0.168-inch radius, 60-degree angle configuration of a helicopter rotor blade nose cap can be accomplished in a one-step process, whereas preforming of this material is necessary to avoid cracking with static force application alone.

2. Ultrasonically assisted forming offers no significant benefits in the forming of nickel 200 sheet material. The yield strength of the material is low enough that forming to the required configuration can be achieved with static forming alone without ultrasonic application.

3. Ultrasonic forming of a high-strength stainless steel such as AM355-CRT offered no significant benefits over static forming because the combined static and dynamic forces were not sufficient to overcome the yield strength of this material at the available 4000-watt ultrasonic power level. Higher ultrasonic powers would be required to achieve significant benefits with this high-yield-strength material.

4. The scuffing and burnt pits on the ultrasonically formed surfaces as evaluated by Hughes Helicopters all occurred outside the critical nose radius and were attributed to die and punch pickup from the materials being formed, which were not removed between formings. Such die pickup would not be encountered with a lubricated dynamic system for forming the nosecaps.

5. Dynamic ultrasonic forming to the nosecap configuration using an ultrasonic system mounted on an appropriately designed drawbench appears to be feasible.

6. It is recommended that ultrasonic forming of titanium alloy be considered for other applications involving the forming of this material for aircraft surfaces.

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Technical Report AVRADCOM TR 81-F-3
January 1981, illus-tables, Contract DAAG 46-79-C-0001,
D/A Project 1777052, AMCMS Code 1497-90-7-57052
Final Report, December 1978-November 1980

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Nickel

Ultrasonic forming was investigated as a means for shaping aircraft sheet materials, including titanium 6A1-4V alloy, nickel, and stainless steel AM355-CRT, into a helicopter rotor blade nosecap contour. Equipment for static forming of small coupons consisted of a modified 4000-watt ultrasonic spot welder provided with specially designed punch and die sets. The titanium alloy was successfully formed to a 60-degree angle in one step with ultrasonics, but invariably cracked under static force alone. Nickel had a low enough yield strength that it could be successfully formed either with or without ultrasonics. Insufficient ultrasonic power was available to produce beneficial effect with the high-strength steel. From analogy with commercially used ultrasonic tube drawing, it was postulated that dynamic forming of long lengths of the nosecap geometry could be achieved with an ultrasonic system mounted on a drawbench. It was recommended that the ultrasonic technique be considered for forming other aircraft sheet geometries, particularly involving titanium alloy.

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